Massive Star Evolution Through the Ages

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Abstract. We review the current basic picture of the evolution of massive stars and how their evolution and structure changes as a function of initial mass. We give an overview of the fate of modern (Pop I) and primordial (Pop III) stars with emphasis on massive and very massive stars. For single stars we show how the type of explosions, the type of remnant and their frequencies changes for different initial metallicities.

1 Massive star evolution

As massive stars we denote those that are born with initial masses of more than about $8\,\mathrm{M}_\odot$, the minimum mass for single stars to explode as supernova. Once the star has formed, its center generally evolves to increasing central density and temperature. This overall contraction is interrupted by phases of nuclear fusion — hydrogen to helium, helium to carbon and oxygen, then carbon, neon, oxygen and silicon burning, until finally iron is produced and the core collapses. Each fuel burns first in the center, then in a shell. In Table 1 we summarize the burning stages and their durations for a $20\,\mathrm{M}_\odot$ star and in Figure 1 we show the evolution of the interior structure of a $22\,\mathrm{M}_\odot$ star. The time scale for helium burning is about ten times shorter than that of hydrogen burning, mostly because of the lower energy release per unit mass. However, the time scale of the burning stages beyond central helium-burning is radically reduced by thermal neutrino losses that carry away energy *in situ*, instead of requiring that it be transported to the stellar surface. These losses increase with temperature, roughly $\propto T^9$. (See [35] for a more extended review.) When the star has built up a large enough iron core, exceeding its Chandrasekhar mass, it collapses to form a neutron star or a black hole. A supernova explosion may result [11], or even, in rare cases, a gamma-ray burst [23,24].

2 Modern massive stars fates

In Figure 2 we show the fate of modern stars, formed from a composition comparable to that of our sun (Pop I), as a function of initial mass. Below $\sim 8\,\mathrm{M}_\odot$

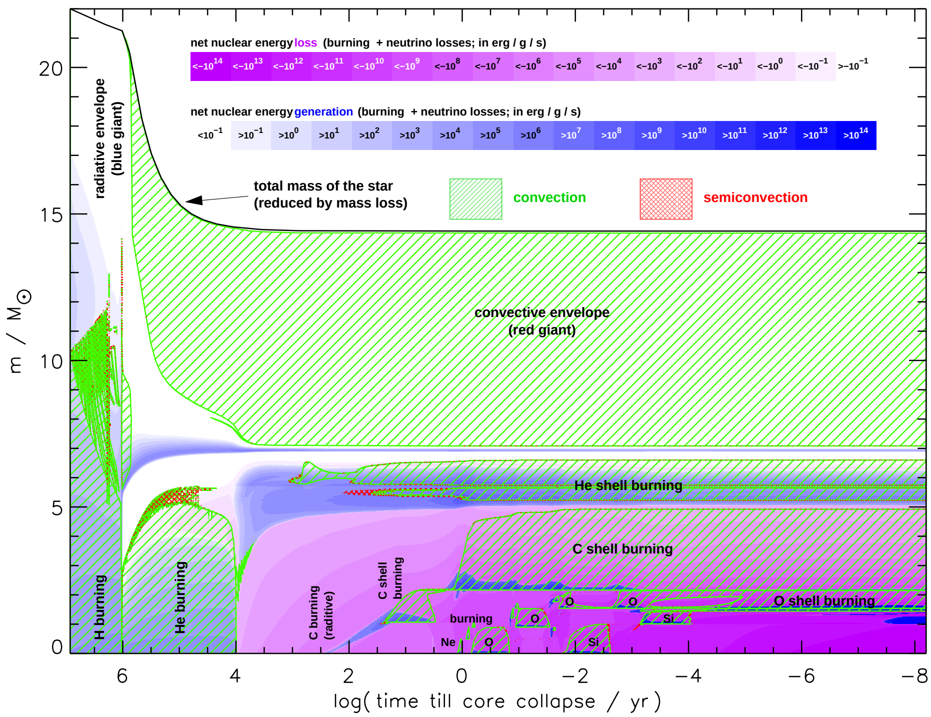

Fig. 1. Interior structure of a 22 M$_\odot$ star of solar composition as a function of time (logarithm of time till core collapse) and enclosed mass. *Green hatching* and *red cross hatching* indicate convective and semiconvective regions. *Blue shading* indicates energy generation and *pink shading* energy loss. Both take into account the sum of nuclear and neutrino loss contributions. The *thick black line* at the top indicates the total mass of the star, being reduce by mass loss due to stellar winds. Note that the mass loss rate actually increases at late times of the stellar evolution. The decreasing slope of the total mass of the star in the figure is due to the logarithmic scale chosen for the time axis.

initial mass only white dwarfs are formed, neon-oxygen white dwarfs immediately below this limit, and carbon-oxygen white dwarfs at even lower masses. The envelope of such stars is lost during their AGB stage.

The regime of initial masses above $\sim$ 8 M$_\odot$ we refer to as *massive stars*. Except for the pair-instability supernovae discussed below They leave behind compact remnants. Up to an initial mass of $\sim 20 - 25$ M$_\odot$ [10,11] typically neutron stars result. The layers above the neutron star are ejected, consisting of the ashes of the preceding hydrostatic stellar burning phases and explosive burning products (*green cross hatching* indicates partial helium burning, i.e., mostly C and O; *solid green* indicates pure metals, i.e., products of complete helium burning and later burning phases).

At higher masses a large fraction of the core can fall back onto the neutron star after an initial explosion has first driven the matter outward. If the resulting remnant mass exceeds the maximum mass for a neutron star, it collapses to a black hole. In Figure 2 we indicate this region by “fallback” and “black hole”.

The evolution of modern massive stars is significantly affected by mass loss due to stellar winds. The mass loss [27] can become so strong that the final mass of the star may actually decrease as its initial mass increases. Indeed, [35] find a maximum in the final mass around $\sim 20\,\mathrm{M}_\odot$. In Figure 2) the *blue curve* shows the final mass at the time of core collapse for massive stars. Around $\lesssim 35\,\mathrm{M}_\odot$ the mass loss becomes so strong that entire hydrogen envelope is lost prior to explosion of the star: in Figure 2 the curve for the final mass of the star intersects the curve for helium core mass at core collapse. The exact mass where this happens depends on, e.g., the uncertainty of the mass loss rates and can vary with initial stellar rotation [31,30,26,20,15,22,21].

Once the massive stars have lost their hydrogen envelope, they become Wolf-Rayet (WR) stars. The mass loss of these objects is known to be large, but also quite uncertain. Recently, the introduction of “clumping” into modeling of Wolf-Rayet star spectra lead to a reduction of the derived mass loss rates by a factor 2-3 [13]. In Figure 2 we show for both cases remnant mass and stellar mass at core collapse: the *dotted lines* are for the case of the previously assumed high mass loss rates and the *dashed lines* for the case of the lowered Wolf-Rayet mass loss rates. In the former case, there may be a regime of initial masses in which the core mass at the time of explosion is low enough to form neutron stars, while it is absent in the other case. The final masses may be higher than indicated in the figure if the star is covered by a hydrogen envelope for a significant fraction of central helium burning [6].

Note that the Wolf-Rayet stars can already release products of central helium burning by stellar winds before explosion (*green hatching* above the *dashed blue curve* indicating the final mass of the star) – or even if they do not explode. Such objects are denoted as WC and WO stars. Here we show the metal production only for the case of the low WR mass loss rate.

Table 1. Nuclear burning stages in massive stars. We give typical temperatures and time scales for a $20\,\mathrm{M}_\odot$ star (Pop I; similar in Pop III) and a $200\,\mathrm{M}_\odot$ star (Pop III)

Burning stages		$20\,\mathrm{M}_\odot$ star		$200\,\mathrm{M}_\odot$ star	
Fuel	Main product	T (10^9 K)	duration (yr)	T (10^9 K)	duration (yr)
H	He	0.037	8.1×10^6	0.14	2.2×10^6
He	O, C	0.19	1.2×10^6	0.24	2.5×10^5
C	Ne, Mg	0.87	9.8×10^2	$1.1^\dagger$	4.5
Ne	O, Mg	1.6	0.60	$2.4^\dagger$	1.1×10^{-6}
O	Si, S	2.0	1.3	$3.5^\dagger$	3.5×10^{-8}
Si	Fe	3.3	0.031	$4.3^\ddagger$	2.7×10^{-7}

†central radiative implosive burning ‡incomplete silicon burning at bounce

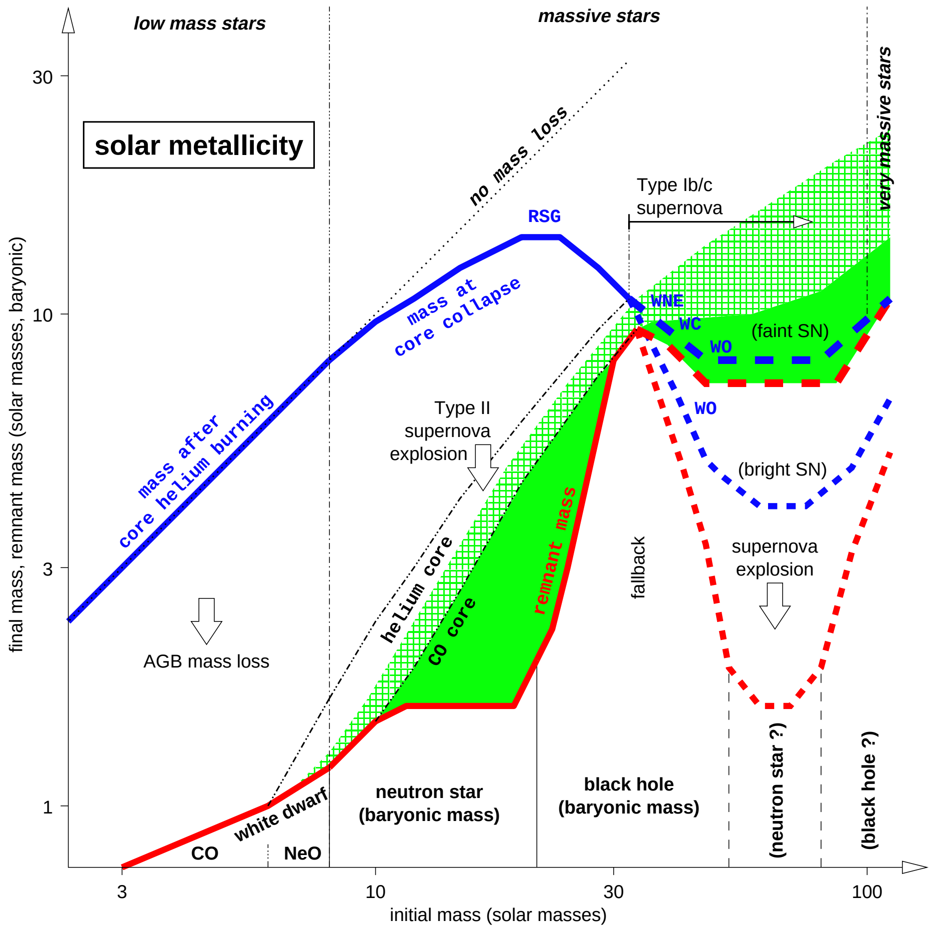

Fig. 2. Stellar mass at time of final explosion/remnant formation (*blue line*), remnant mass (*red line*) and metals released (*green fill* and *hatching*) as a function of initial mass of the star for modern stars (Pop I)

3 Primordial stars

The lack of initial metals in stars that form from the composition as made in the big bang results in a strongly reduced mass loss, down to the point of negligibility [19]. For simplicity, we can therefore assume that Pop III stars keep almost all of their initial mass through the end of central helium burning (Figure 3; see also [25]). Recent studies indicate that the first generation of stars may have been rather massive [4,5,1], or may have had at least a very massive component [28] compared to modern stellar populations. But even those stars might keep most of their initial mass till the end of their evolution [2,14].

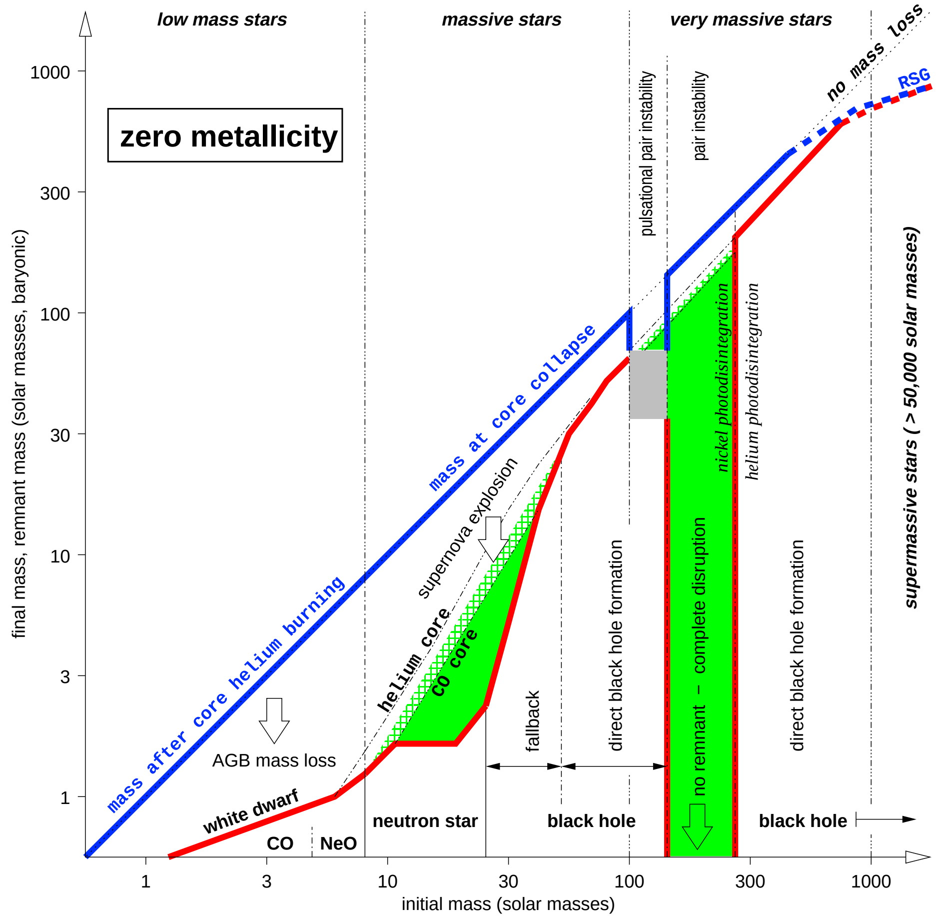

Fig. 3. Stellar mass at time of final explosion/remnant formation (*blue line*), remnant mass (*red line*) and metals released (*green fill and hatching*) as a function of initial mass of the star for primordial (metal-free, Pop III) stars

For masses below $\lesssim 35\,\mathrm{M}_\odot$ the fate of the stars is similar to that of modern stars (Figure 2) except that the mass at core collapse continues increasing. Low-mass stars form white dwarfs, massive stars first form neutron stars, then black holes by fall back. However, as the helium core mass at core collapse increases, eventually a successful supernova shock cannot be launched due to the strong infall of the increasingly larger oxygen and silicon core masses. A black hole is formed directly and no supernova explosion should occur.

Above an initial mass of $\sim 100\,\mathrm{M}_\odot$, the stars encounter the electron-positron pair creation instability after central carbon burning [3,34]. This leads to rapid burning of oxygen and silicon (Table 1). Only when enough energy is released, the infall is stopped and reverts into an explosion. Below an initial mass of $\sim 140\,\mathrm{M}_\odot$ the explosion energy is not big enough to disrupt the entire star. The outer layers, the hydrogen envelope and maybe part of the helium core, however, are ejected. The rest of the star falls back and may encounter subsequent pulses of this kind within one to several 10,000 yrs until it finally collapses and directly forms a black hole. These stars will not have a hydrogen envelope at the time of collapse, but the ejecta may still be close by. The energy of these eruptions can be as high as 3×10^{51} erg.

For initial masses from $\sim 140-260\,\mathrm{M}_\odot$ the explosion energy of the first pulse is already sufficient to entirely disrupt the star. In this case no remnant remains and all the metals are ejected. The explosion energies may reach $\sim 10^{53}$ erg and more than $50\,\mathrm{M}_\odot$ of radioactive ^{56}Ni may be ejected – both figures are close to 100× that of Type Ia supernovae. These events are rather bright and could be observable out to the edge of the universe in the infrared [16]. Further observational signatures should be their long time scale, already in their rest frame, but additionally boosted by their high redshift, and a Lyman-alpha cut-off corresponding to their redshift, as they should explode when most of the universe is not yet re-ionized.

Above initial masses of $\sim 260\,\mathrm{M}_\odot$ photo-disintegration of alpha-particles (which themselves are already the result of photo-disintegration of iron group elements which were made in silicon burning) reduces the pressure enough that the collapse of the star is not turned around but directly continues into a black hole [34,12]. Probably no metals are ejected in this case. Above several $100\,\mathrm{M}_\odot$ even primordial stars may evolve into red supergiants, becoming pulsationally unstable and lose mass [2]. Since we have no good estimate of the associate mass loss, we draw the line for the pre-collapse and remnant mass as dashed lines in this regime.

4 Supernova and remnant populations

In Figures 4 and 5 we try to give a rough sketch of the remnant and supernova types as a function of initial mass and metallicity. A very detailed description will be given in [17]. Due to the uncertainty of some mass loss rates and their scaling with metallicity, in particular those of red supergiants and Wolf-Rayet (WR) stars, we do not give an absolute scale on the *y-axis* of these figures, but assume that we can at least outline the rough sequence of populations with increasing metallicity.

Only at sufficiently low metallicities do very massive stars keep all their mass till collapse. As metallicity increases, due to increasing mass loss, first the very massive stars that directly collapse to black holes disappear. Next the pair-instability supernova produce less and less powerful explosions until they disappear. Above the metallicity limit for pair instability all very massive single stars should leave compact remnants. There may be a regime in which pair-instability supernovae can occur in bare helium stars if the hydrogen envelope has been carried away by stellar wind, but the helium core has not been shrunk

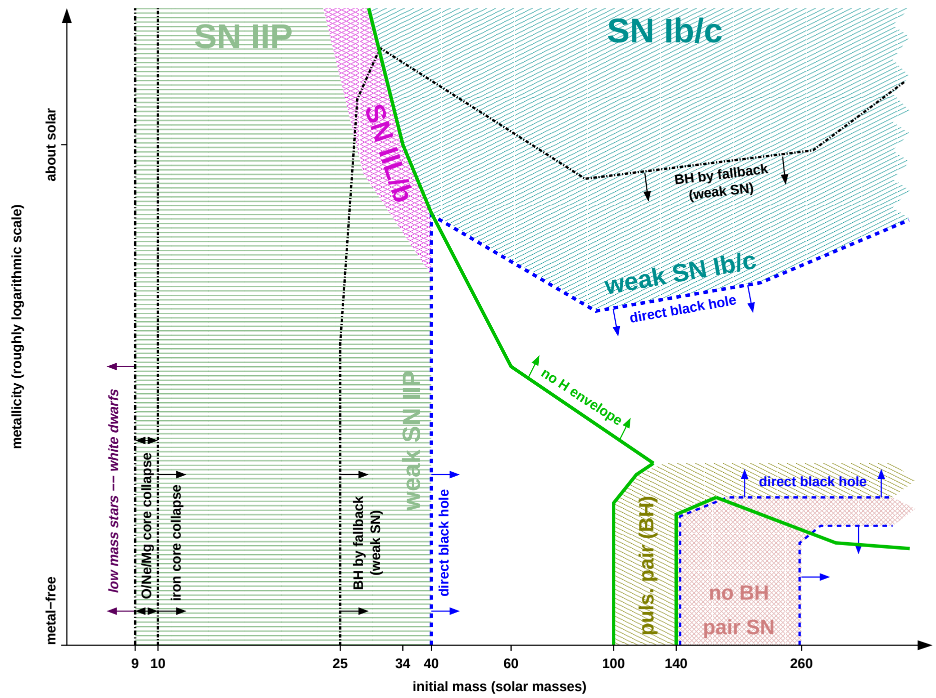

Fig. 4. Supernova types of single stars as a function of stellar initial mass and metallicity. *White regions* show where no supernova explosion is expected. *green horizontal hatching* indicates Type IIL supernovae, *purple diagonal hatching* Type IIb supernovae, *dark green diagonal hatching* Type Ib/c supernovae, and *light green diagonal hatching* and *red cross hatching* indicate pulsational and non-pulsational pair-instability supernovae. The *green curve* is the dividing line between stars that have a hydrogen envelope (below the *green line*) and those that don't.

enough by WR winds. At higher metallicities also the pulsational pair-instability supernovae will disappear. They should always collapse as hydrogen-free stars ("window" in the *green curve* indication the presence/loss of the hydrogen envelope) and their core collapse produces a black hole without launching a supernova explosion. Depending on whether stellar winds have uncovered the helium core before collapse due high enough metallicity or just the pair instability pulsations ejected the hydrogen envelope, the hydrogen may still be in the vicinity of the star or be blown far away.

If mass loss does not uncover the helium core, above $\sim 40\,\mathrm{M}_{\odot}$ black holes are formed directly. In this case we do not expect a supernova explosion display. For stars massive enough, the hydrogen envelope is likely removed by stellar winds, shrinking the stellar core. Since the core collapse and explosion are mostly determined by the core masses, this alters the fate of those stars. This means that above a certain metallicity (and as function of their initial mass) even stars above the direct black hole limit for hydrogen-covered stars, can avoid directly forming

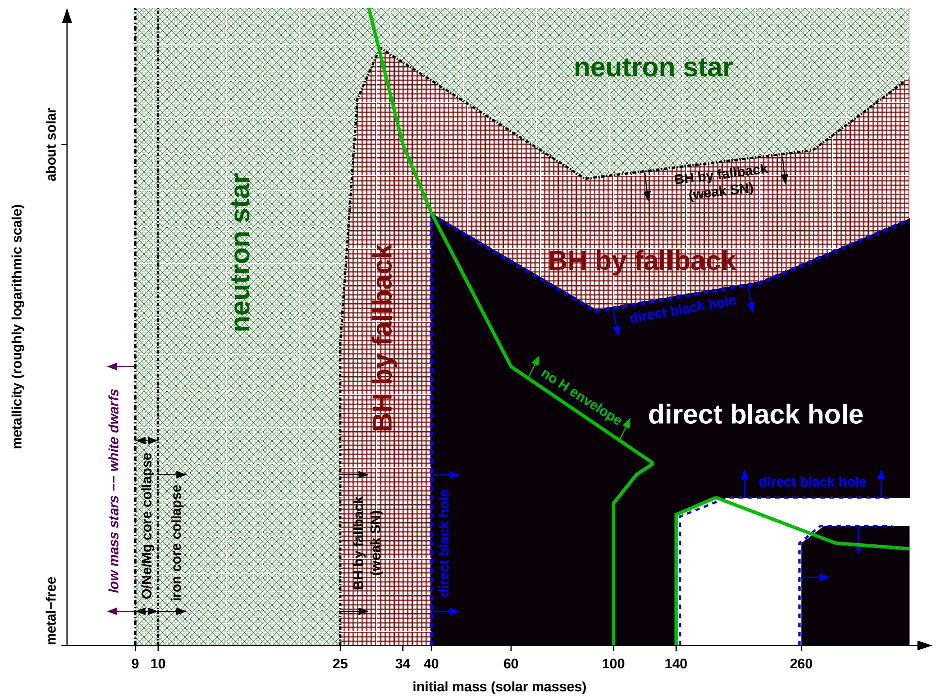

Fig. 5. Stellar remnants of single stars as a function of stellar initial mass and metallicity. *Green diagonal cross hatching* indicates the where neutron stars are made, *red horizontal and vertical cross hatching* indicates regimes where black holes are formed by fall back and *solid black* shows where black holes form directly without launching a supernova shock from a proto-neutron star. In the *white region* at low metallicity and high mass no remnant is left (pair instability supernovae) and in the *white region* on the left hand side white dwarfs are made. We use the same curves and dividing lines as in Figure 5.

black holes (Figure 4) and may result in hyrogen-free supernova explosions of Type Ib or Ic [8,9] (Figure 4).

At even higher metallicity, also the limit for black hole formation due to fallback can be avoided in hydrogen-free stars. That is, for high enough metallicity, all stars may result in neutron stars (Figure 5). Those supernovae, resulting from smaller cores, are potentially brighter than those from the more massive hydrogen-free stars [7] (except pair-instability supernovae).

In stars that keep the hydrogen envelope, down to $\sim 20-25\,\mathrm{M}_\odot$ the fallback may be big enough to form black holes [10], but yet a Type II supernova [8] may occur. If the fallback is excessive, the supernova may be dim. Below this mass limit neutron stars are made. Stars that have lost most of their hydrogen envelope but about $\lesssim 1\,\mathrm{M}_\odot$ at the time of core collapse may result in Type IIL/b supernovae, while those that have left more hydrogen will make Type IIP supernovae (see also [8,9]). Naturally, in Figure 4 the Type IIL/b supernovae thus occur in a small stripe just below the limit for complete loss of the hydrogen envelope, as a function of mass and metallicity. Since this curve goes above the limit for successful core collapse supernova explosions at low metallicity, we anticipate that there will be a lower metallicity limit for Type IIL/b supernovae from single stars.

5 Summary and discussion

We outlined, in a rough scheme, the fate of modern and primordial massive single stars as a function of their initial mass and metallicity. The most important difference caused by the variation of compositions is the strong mass loss in modern stars. Because of this, they may lose their hydrogen envelope above a certain initial mass. When this happens, the exposed helium star may cause even stronger mass loss. Only at very low metallicity can very massive stars can retain enough mass to become pair-instability supernovae. On the other hand, certain types of supernovae that require the loss of most or all of the hydrogen envelope, occur in single stars only above a certain level of metal enrichment.

The lines between the different regimes in Figures 2–5 are only a rough guidance. Due to the interaction of different burning shells (Figure 1) the core masses (silicon core, iron core, etc.) do not increase monotonously as a function of initial mass or metallicity [35,17]. Therefore one cannot expect a unique transition from one regime to the neighboring, but a rather ragged one, with detached "islands" of one regime within the other.

In contrast to single stars, interacting ("close") binary stars can lead to the loss of the hydrogen envelope even in metal-free stars. Therefore, unfortunately, hydrogen-free stars and supernovae can be present at any metallicity, and thus an observational determination of the metallicity limit for the loss of the hydrogen envelope from low metallicity stellar populations is rendered difficult. However, the ratio of supernova types may change when single stars start contributing to Type IIL/b, and Ib/c supernovae. Depending on the initial separation and mass ratio of the binary, the mass exchange can happen at different evolution stages (most prominent: during hydrogen burning, during the transition from hydrogen burning to helium burning, and during or at the end of helium burning). The earlier the mass transfer happens, the smaller is the final mass of the star.

Finally, the evidence for an association of gamma-ray bursts (GRBs) with massive star populations seems to increase [18]. Provided a star that collapses to a black hole has sufficient angular momentum, it may launch a jet [33], blowing up the star (e.g., [24]; "hypernova", see also [29]) and possibly producing a GRB if the jet escapes the star [33,23,37,36]. If any single star can ever have sufficient angular momentum at core collapse, in Figure 5 only in the "black hole by fallback" and "direct black hole" regimes such events can occur. And only above the line for loss of the hydrogen envelope, GRBs could be made.

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